

Experimental Results of Mass and Energy Yield Referred to Different Torrefaction Pathways

M. Grigante · D. Antolini

Received: 26 July 2012 / Accepted: 4 February 2013 / Published online: 14 February 2013
© Springer Science+Business Media Dordrecht 2013

Abstract

Purpose The aim of this work is to investigate the influence of temperature and time on the final quality of torrefied biomass. In particular this study analyses the influence of different time–temperature pathways in reaching selected values of Mass Yield Ratio (M.Y.R.) by applying torrefaction treatment on samples of spruce pine. This represents an innovative approach as, making reference to the majority of the published works, M.Y.R. is not considered an independent parameter but a result of random conditions with temperatures ranging from 240 to 300 °C and duration arbitrary selected within few minutes to 1–2 h. For the investigated torrefied samples, energy parameters as high heating value, energy densification ratio, energy yield besides ultimate analysis are therefore determined.

Method The experimental investigation is carried out on a small plant located at the Thermochemical Biomass Energy Laboratory of the University of Trento. The core of the plant is a batch reactor that can accept a load approximately of 50 g of biomass. The reactor is directly fluxed by a controlled nitrogen flow of 40 l min^{−1} (SPT) heated by an electrical resistance at selected temperatures of 265, 280, 295, 310 °C. A single type of biomass, spruce pine, has been utilized as highly available from local sawmill residues. The size of samples are in the range from 9.50 to 30 mm in length/width and 5.60 to 9.50 mm in thickness. For 7 samples the cited properties are determined by selecting suitable temperature–time pathways.

Results This investigation details in terms of the main process parameters, temperature and time, the thermochemical changes involving the selected raw biomass when submitted to selected torrefaction treatment. As main result this study demonstrates that samples reaching the same M.Y.R. present almost the same values for the forementioned properties, even if the final state of the samples refers to different torrefaction process pathways.

Conclusion From the proposed experimental investigation it can be deduced that, within the selected temperatures range, the torrefaction pathway imposed to reach a selected value of M.Y.R. has no impact on the final energy parameters of the torrefied biomass. These properties seem to be dependent on the imposed value of the M.Y.R. so that it can therefore be regarded as a synthetic state parameter for this thermal process.

Keywords Mass yield ratio · Energy yield · Thermal pathway · Torrefaction parameters

Introduction

In recent years torrefaction has been recommended as an interesting way to valorise biomass properties. During this process, that consists in subjecting biomass to a mild thermal treatment between 200 and 300 °C in absence of oxygen [1], the cell walls of the lignocellulosic structure are degraded and the final product lies between those of wood and charcoal. The main modifications on biomass characteristics have been widely investigated through numerous recent studies: effects on property and structure variations [2], consequences on mechanical properties and grindability [3, 4], fungal durability [5], reduction on hygroscopicity and subsequent shrinkage decrease [6].

M. Grigante (✉) · D. Antolini
Department of Civil and Environmental Engineering,
University of Trento, Via Mesiano 77, 38123 Trento, Italy
e-mail: maurizio.grigante@ing.unitn.it

Several studies have investigated the enhanced combustible properties of torrefied biomass [7, 8]. The energy quality of the torrefied product is expressed in terms of significant parameters as High Heating Value (H.H.V.), Energy Densification Ratio (E.D.R.) and Energy Yield (E.Y.). The estimation and/or the experimental determination of these parameters is of utmost importance both for the torrefaction plants design and for the final optimization analysis involving the biomass value chain between the raw material to the final products. Wide ranging reviews comparing and compiling different studies on torrefaction have been recently published [9, 10]. From a general point of view, the cited papers make evidence that, even if this thermal pre-treatment has known only in the last years a growing interest, a huge amount of experimental data have just been produced. From a more detailed point of view it emerges that, in spite of the relevant experimental effort, the road map of most of the studies till now carried out has investigated the effects of time (duration effects) and temperature (heating effects) on the final product as result of a random selection of these two parameters (temperature and time). New approaches have been recently proposed to retrace the combined effects of temperature and duration [11]. Considering the actual state of art of this technology, the urgent question concerns the evaluation of the effective role of these two key parameters on the final quality of the torrefied biomass. This work focuses on assuming the M.Y.R. as the characterising parameter of the process and demonstrates that the time–temperature pathway has no impact on the energy parameters of the final torrefied product. This means that samples having reached the same M.Y.R. present also the same values of both H.H.V. and Ultimate Analysis (U.A.) independently from the process pathway followed to reach it. This work extends and enhances the results of previous studies involving a similar investigation approach [11, 12]. The significant improvement of this study is that the M.Y.R. can be assumed as a synthetic indicator that characterizes the energy parameters of the torrefaction process insomuch to be assumed as a state parameter. This work has to be considered as part of an ongoing research. Further studies will extend this approach to confirm the effectiveness of the M.Y.R. as a synthetic parameter also for other relevant properties as hygroscopicity and grindability.

Materials and Methods

Material Selection and Preparation

For the proposed investigations a single type of biomass, spruce pine, has been selected as highly available from local sawmill residues. The size of samples was reduced in

order to obtain particles in the range from 9.50 to 30 mm in length/width and 5.60 to 9.50 mm in thickness. These dimensions, besides guarantee the same mean size for all the tests, correspond to the chips size usually utilized on wood-stove heating apparatuses. The selected specimens are defect-free, bark-free, without knots, have a high degree of uniformity and are representative of the core part of the trees. Prior to torrefaction treatment, the biomass feedstocks are maintained under laboratory conditions, then oven dried at 105 °C (± 3 °C) during 24 h in order to determine the oven-dry mass of the raw biomass and finally stored under dry conditions in desiccators containing silica gel. Throughout this study the dried raw material is used as reference state for comparison with respect to the achieved torrefied samples. Until and after the thermal treatment the oven-dry mass of the samples has been measured to the nearest 10^{-4} g with a digital balance. Processed feedstocks have been accurately prepared in order to guarantee the homogeneity of the samples to be analyzed. Details of the processed data are reported on the “[Results and Discussion](#)” section dedicated to results presentation.

Torrefaction Equipment

For the proposed experimental activity a dedicated device has been developed at the Thermochemical Biomass Energy Laboratory (TheBEL) of the University of Trento. It consists of a vertical fixed bed reactor made of a stainless steel tube with a diameter of 56 mm and a length of 200 mm. These dimensions refer to the inside tube of the scheme depicted on the following Fig. 1. The biomass sample is loaded by removing the upper part of the reactor that, during the test, is hermetically sealed by a suitable screw device. To hold the sample a distributor plate is located at 50 mm above the bottom. The atmosphere inside the reactor is controlled by a nitrogen flow rate that maintains the inert conditions by reducing the O₂ level, during each test, at 0.0 ± 0.001 %. This level is measured on the gas leaving the reactor by an electrochemical sensor equipped on an emission monitor system (MRU GmbH Delta 1600). Reasonably, this enables such a low O₂ level throughout the whole reactor chamber. The continuous nitrogen flow feeds the reactor from the bottom at a rate of 40 ± 0.20 l min⁻¹ (STP,) and is kept constant by an electronic flow controller in conjunction with a controller readout (*Bronkhorst*). Before entering the reactor the nitrogen is directly heated by an electrical resistance (Leister Mini Sensor 800W) and its temperature controlled by a PID controller. This direct heating option, in conjunction with the selected flow rate, ensures a high heat exchange coefficient reducing hence the temperature differences between gas and sample and contributes to achieve a thermal profile as much as possible homogeneous

throughout the whole sample itself. Besides maintaining the inert conditions, the nitrogen flow acts as a sweep rapidly carrying the torrefaction products out of the reactor. Several temperatures, whose values are measured using calibrated *k* type thermocouples, are monitored. For sake of clearness, Fig. 1 evidences also the temperature sensors location. Looking at it, the temperature of the sample is monitored by 3 thermocouples (T_2 , T_3 , T_4) symmetrically placed inside the biomass bed from the bottom to the top and located at a half radius distance from the reactor centre. The height of the bed (indicated with B on Fig. 1) is 100 mm while the distance between T_2 and T_4 is 50 mm. For a better control of the temperature inside the reactor chamber, two others thermocouples T_1 and T_5 monitor the in–out nitrogen temperature flow. This monitoring action is extended outside the reactor to detect the ambient and the external reactor surface temperatures (these last ones are not indicated). To enhance the thermal homogeneity of the reactor chamber, dispersions are limited at the bottom and at the top by a high ceramic wool swab insulation extended to the radial surface with a 100 mm thick of the same material. A three-necked flasks device, acting as trapping system, is positioned out of the reactor to collect condensable liquids: the first flask sets in ambient conditions, the second one is immersed on a refrigerant liquid bath, the last one works as a scrubbing unit in water. The remaining non condensable gases flow go through a filter to remove the carbon soot particles before being released in atmosphere. The investigation of tars and permanent gases are outside the aim of this study and therefore not considered further.

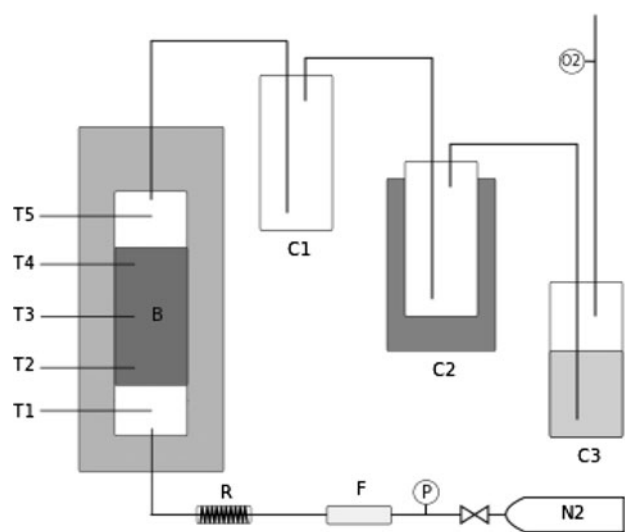


Fig. 1 Scheme of the torrefaction batch reactor: T1–T5, thermocouples; C1, ambient trap; C2, cold trap; C3, water trap; P, pressure measure; F, flow controller; R, electrical resistance; O₂, oxygen detector

Torrefaction Protocol

For each experimental run, the reactor is manually loaded with raw biomass sample roughly weighting 45 g and placed above the distribution plate located inside the reactor. Several heating treatments are conducted at different temperatures ranging from 265 to 310 °C, representative of light to severe torrefaction conditions. It is widely accepted in literature that the onset of primary devolatilization occurs at 200 °C [13, 14]. The period between this temperature being reached and cooling down has been assumed in this study too as “*torrefaction time*” [15] and represented on the following Fig. 2. Once the prepared dry sample is loaded, for each heating treatment the following protocol has been adopted: using an air flow of 40 l min^{−1} (STP) at an heating rate of 16 °C min^{−1}, the temperature of 150 °C is reached. This preliminary step limits the nitrogen consumption. This temperature kept constant for some minutes, the carrier gas line is switched to the nitrogen flow and, maintaining the same heating rate, the new temperature set point, fixed at 190 °C, is reached. This step allows to achieve the highest temperature on the whole reactor structure avoiding combustion risk and devolatilization reactions. This temperature is kept constant for about 13–15 min before moving to the selected torrefaction temperature which is maintained for the required torrefaction time. After this time has been reached, heating device is turned off and the continuous flow of cold nitrogen allows cooling down the sample temperature soon. When the temperature of the reactor chamber is close to ambient temperature the sample is taken out from the reactor and weighted to determine the effective M.Y.R. Some details must be briefly illustrated. The cited *torrefaction time*, indicated in particular on Table 1 (“[Results and Discussion](#)” section), conforms to the assumed definition and corresponds to the effective duration of the torrefaction recorded during each experimental run. The setting of this quantity comes from an extended calibration procedure in order to tie, for the adopted apparatus, the M.Y.R. versus time at selected temperature conditions. These results can be exploited to model a generalized estimation procedure the Authors are still working on as a subject for future dedicated investigations. Regarding the temperature to which the heating protocol evolution is referred, it is representative of the mean value measured by sensors T_2 , T_3 and T_4 (Fig. 1). This mean value is then assumed as the *torrefaction temperature* of the sample during the test. As example, Fig. 2 represents an evolution of this temperature versus time for a complete heating protocol run at a selected torrefaction temperature of 295 °C. For the same test the O₂ concentration evolution is also added. For sake of clearness it is to point out that, for the located sensors placement, the highest temperature,

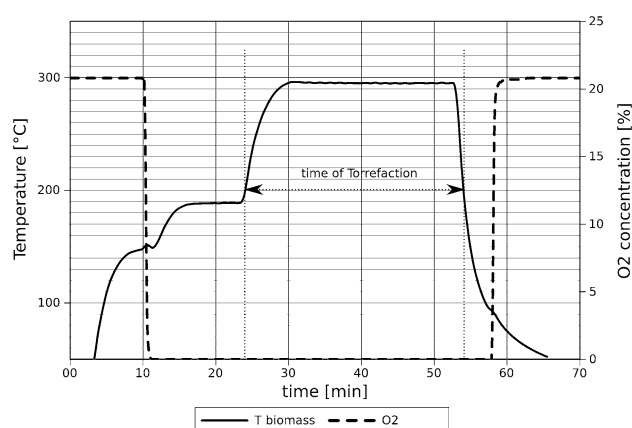


Fig. 2 Temperature and O₂ concentration evolution for a protocol run set at a torrefaction temperature of 295 °C

measured by thermocouple T₂ and the smallest one, T₄, are within ± 4 °C with respect to the indicated torrefaction temperature.

Torrefaction Parameters and Properties

The experimental strategy pursued in this work focuses on selecting some suitable values of M.Y.R. defined as:

Mass Yield Ratio (M.Y.R.)

$$= \frac{\text{mass of dried torrefied biomass}}{\text{mass of dried raw biomass}} \times 100$$

For the proposed study M.Y.R. of 90, 80 and 70 % have been chosen. Four temperatures have been considered within the range previously indicated: 265, 280, 295 and 310 °C. Each of these M.Y.R. conditions can be reached by selecting a couple of temperature–time values respectively. These data available, the Energy Densification Ratio (E.D.R.) and the Energy Yield (E.Y.) quantities can be determined according to the following definitions:

Table 1 M.Y.R. results from light (A1) to severe (A7) torrefaction treatment

Sample	Torrefaction temperature (°C)	Torrefaction time (min)	M.Y.R. Experimental ^a
A0	25 ^b	0	100.0 ^b
A1	265	49	89.3 (0.32)
A2	280	20	89.4 (0.21)
A3	280	76	79.4 (0.38)
A4	295	30	80.2 (0.27)
A5	310	17	79.1 (0.35)
A6	295	92	68.5 (0.40)
A7	310	36	69.0 (0.38)

^a d.a.f dry and ash free

^b Raw biomass

Energy Densification Ratio (E.D.R.)

$$= \frac{\text{H.H.V. of dried torrefied biomass}}{\text{H.H.V. of dried raw biomass}}$$

Energy Yield (E.Y.) = mass yield ratio

$$\times \text{energy densification ratio}$$

The experimental methods and apparatuses utilized to determine the indicated parameters are detailed on the following paragraph.

Results and Discussion

The obtained results are reported on the following Tables 1, 2 and 3. In each table, samples are exposed as follows: raw biomass is indicated as A0 while torrefied samples are progressively nominated on the base of their M.Y.R. value and expressed on a decreasing percentage scale: samples A1, A2 are close to 90 %; A3, A4, A5 to 80 % and A6, A7 to 70 % respectively.

Mass Loss

For each of the indicated samples (A0–A7) Table 1 reports the *torrefaction temperature* and the *torrefaction time* imposed to reach the *experimental* M.Y.R. values reported on a dry and ash free base. As significant remark, it clearly emerges that the same M.Y.R. can be reached by imposing different temperatures and torrefaction duration. As example, an increasing temperature of 30 °C (from 280 °C case A3 to 310 °C case A5) entails a decreasing time of 59 min (≈ 1 h, from 76 min case A3 to 17 min case A5). This means that an increasing temperature of 10.2 % allows a reduction time of 77.6 % to obtain almost the same experimental M.Y.R. The reported results represent the average value based on three replicates for each conditions. The obtained experimental data can be considered of good quality as their uncertainties set within ± 0.4 %.

Energy Properties

For each of the treated samples the H.H.V. has been experimentally measured. Applying the definitions previously introduced for E.D.R. and E.Y., these quantities have been correspondently calculated for the same samples (A0–A7) as well and reported on Table 2. In particular the indicated H.H.V. values represent the average value based on three replicates for each sample. This quantity, also called gross calorific value, has been determined by the bomb calorimetric method (Isoperibolic Calorimeter MOD. IKA C5000). A crucible with a sample containing <1 g biomass material was inserted into the bomb. After closing

Table 2 H.H.V, E.D.R. and E.Y. values of raw wood (A0) and torrefied (A1–A7) samples

Sample	M.Y.R.	H.H.V. ^a (kJ/g)	E.D.R. ^a (%)	E. Y. ^a (%)
A0	100.0 ^b	19.178 (0.322)	100.0 ^b	100.0 ^b
A1	89.3	20.592 (0.127)	107.4	95.9
A2	89.4	20.639 (0.545)	107.6	96.2
A3	79.4	21.294 (0.303)	111.0	88.1
A4	80.2	21.565 (0.112)	112.4	90.1
A5	79.1	21.471 (0.211)	112.0	88.5
A6	68.5	22.677 (0.213)	118.2	80.7
A7	69.0	22.303 (0.160)	116.3	80.1

^a *d.a.f* dry and ash free^b Raw biomass

the bomb it was filled with oxygen (purity 99.99 %) under a pressure of 30 bar. The bomb was placed in the adiabatic calorimetric equipment filled with water and the sample ignited electrically. The resulting increase of the water temperature allows the calculation of the H.H.V. of the sample. The heat capacity of the calorimeter was determined using benzoic acid as reference substance. The reported results confirm the general trend observed for torrefaction treatment widely proved on recent published works [11, 12, 16, 17]. Torrefaction process generates a solid fuel with an increase in H.H.V. and E.D.R. converting therefore raw biomass from a low energy to density into a high energy to density feedstock. As interesting result, the effects induced on samples processed by following different time–temperature pathways can be examined. Considering samples having very close experimental M.Y.R. as A3 and A5, it emerges that similar results follow also for H.H.V. and E.D.R.: H.H.V. for A3 and A5 sets at 21.294 and 21.471 respectively while corresponding values for E.D.R. set at 111 for A3 and 112 for A5. Due to E.Y. definition, the same trend is maintained for this parameter too: 88.1 for A3 and 88.5 for A5. Similar remarks can be drawn down looking at samples having similar M.Y.R. as

A1, A2 or A6, A7 and so on. For sake of clearness this global trend is highlighted on the following Fig. 3: even if the thermal pathway can be completely different in terms of *torrefaction temperature* and *torrefaction time*, samples reaching the same M.Y.R. present almost the same E.Y. value.

Chemical Properties

The proposed experimental investigation has been improved by determining, for the examined samples, the U.A. and the corresponding ash content. For wood prior and after thermal treatment ash content has been determined using the standard method DD CEN/TS 14775:2004 [18].

For both raw and torrefied samples U.A. has been performed with an elemental analyzer (Mod. Vario Macro Cube–ELEMENTAR) for full determination of C, H, N, S, and O as difference. It works in oxygen atmosphere by charging about 2–3 mg of sample that are incinerated at 1,000 °C and the final reaction products CO₂, H₂O, N₂ and SO₂ quantitatively determined by gas chromatography detector. Utilizing the same presentation scheme previously adopted, the results are reported on the following Table 3. For this type of analysis, a standard representation based on the elements atomic ratios H/C versus O/C has been depicted on the Van Krevelen diagram, Fig. 4. As expected, torrefaction treatment increases carbon content and reduces the oxygen amount. Data reported on Table 3 confirm, for the chemical species too, the remarks deduced for energy properties: samples having the same M.Y.R. present also similar results for U.A. and ash content. This is clearly evidenced on the Van Krevelen representation where atomic ratios for torrefied samples having the same M.Y.R. are almost undistinguishable. On the same Fig. 4 data for peat, bituminous, lignite and anthracite coal available from ECN database [19] are also reported. It is evident that the more severe the torrefaction treatments are

Table 3 Ultimate analysis, ash content and corresponding elements atomic ratios for raw wood (A0) and torrefied samples (A1–A7)

Sample	Dry and ash free mass (%)						Element ratios	
	C	N	H	S	O*	Ash	O/C ratio	H/C ratio
A0	47.66 (0.02)	0.14 (0.04)	6.32 (0.01)	0.11 (0.08)	45.49	0.28	0.715	1.591
A1	52.34 (0.15)	0.20 (0.06)	5.99 (0.02)	0.02 (0.00)	41.15	0.30	0.589	1.373
A2	52.44 (0.06)	0.17 (0.03)	6.00 (0.03)	0.01 (0.00)	41.05	0.33	0.587	1.372
A3	54.50 (0.22)	0.19 (0.02)	5.82 (0.03)	0.01 (0.00)	39.10	0.38	0.538	1.281
A4	54.65 (0.08)	0.19 (0.04)	5.86 (0.02)	0.01 (0.00)	38.96	0.35	0.534	1.286
A5	54.57 (0.05)	0.21 (0.03)	5.83 (0.01)	0.00 (0.00)	39.02	0.37	0.536	1.282
A6	57.49 (0.11)	0.21 (0.04)	5.64 (0.01)	0.00 (0.00)	36.20	0.45	0.472	1.177
A7	57.07 (0.16)	0.25 (0.02)	5.64 (0.01)	0.00 (0.00)	36.59	0.45	0.480	1.185

* Obtained as difference

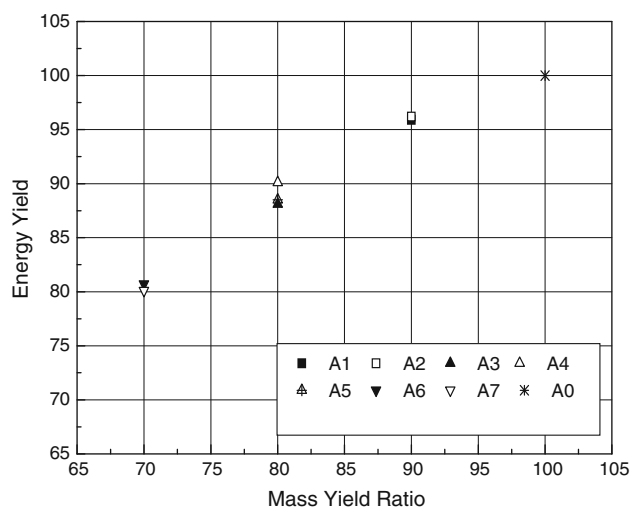


Fig. 3 Energy Yield versus Mass Yield Ratio for raw wood and torrefied samples

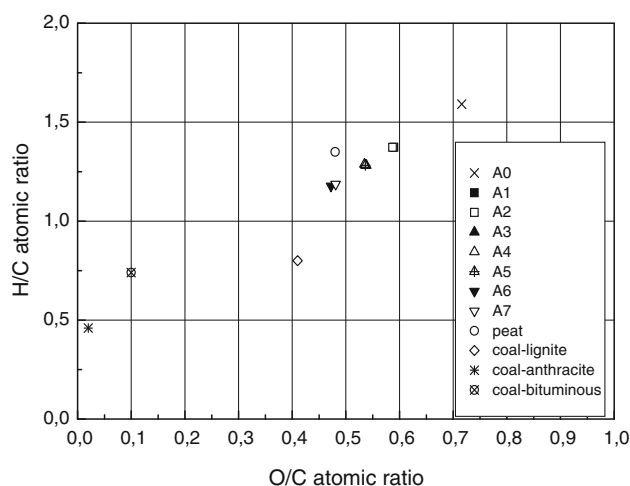


Fig. 4 Van Krevelen diagram for the examined samples and others compounds [12]

the more the quality of the torrefied biomass approaches lignite coal.

Experimental Data Analysis

Although the experimental tests carried out during this investigation have produced a relevant amount of experimental data, they are not sufficient for a significant statistical analysis. The accuracy of the obtained measurements has been however determined in terms of *absolute deviation* expressed as the absolute difference between the point value and the mean value of the corresponding data set. For the experimental properties, these values are reported in parentheses on Tables 1, 2 and 3 as *mean absolute deviation* observed for the repeated analyses of each of the A0–A7 data set.

Conclusions

The proposed study formulates an innovative approach to investigate the torrefaction process. The aim of this work consists in determining the effective role of temperature and time as fundamental parameters for this thermal process. Basing it on a detailed experimental campaign, this study demonstrates that the final H.H.V. and U.A. values of a torrefied samples can be brought back to their corresponding M.Y.R. without making reference to the specific time–temperature process pathway. This means that a torrefied sample can be considered, for the cited properties, as having reached a state condition and can be characterized in term of M.Y.R. as synthetic parameter. The proposed investigation confirms and enhances therefore the prevailing role of M.Y.R. in characterizing torrefaction process as highlighted also on previous studies [6, 11, 12]. These results are intended to be used in decision-making process strategy including in particular process optimization. At the same time the proposed approach looks interesting to be extended to the whole biomass value chain from the pre-treatment transformations as torrefaction to high added value chemicals and energy processes.

Acknowledgments We gratefully acknowledge financial support from the F.T.U. (Trentino University Foundation) and the collaboration with Consortium C.A.R.e.S. (Research and Development Artisan Consortium). The Authors wish to thank Dr. R. Marconi of EMME3 Laboratory for his support in U.A. and H.H.V. determination.

References

- Bourgeois, J.P.: Thermocondensed lignocelluloses materials and a method and an oven for obtaining it. US Patent 4, 816, 572 (1989)
- Chen, W.H., Lu, K.M., Tsai, C.M.: An experimental analysis on property and structure variations of agricultural wastes undergoing torrefaction. *Appl. Energy* **100**, 318–325 (2012)
- Unsal, O., Ayrimis, N.: Variations in compression strength and surface roughness of heat-treated Turkish river red gum (*Eucalyptus camaldulensis*) wood. *J. Wood Sci.* **51**, 405–409 (2005)
- Phanphanich, M., Mani, S.: Impact of torrefaction on the grindability and fuel characteristics of forest biomass. *Bioresour. Technol.* **102**, 1246–1253 (2011)
- Hakkou, M., Petrisans, M., Gerardin, P., Zoulalian, A.: Investigation of the reasons for fungal durability of heat-treated beech wood. *Polym. Degrad. Stab.* **91**, 393–397 (2006)
- Almeida, G., Brito, J.O., Perré, P.: Changes in wood-water relationship due to heat treatment assessed using micro-sample of *Eucalyptus*. *Holzforchung* **63**(1), 80–88 (2009)
- Lu, K.M., Lee, W.J., Chen, W.H., Liu, S.H., Lin, T.C.: Torrefaction and low temperature carbonization of oil palm fiber and eucalyptus in nitrogen and air atmospheres. *Bioresour. Technol.* **123**, 98–105 (2012)
- Rousset, P., Aguiar, C., Labbé, N., Commandré, J.M.: Enhancing the combustible properties of bamboo by torrefaction. *Bioresour. Technol.* **102**, 8225–8231 (2011)

9. Chew, J.J., Doshi, V.: Recent advances in biomass pretreatment—torrefaction fundamentals and technology. *Renew. Sustain. Energy Rev.* **15**, 4212–4222 (2011)
10. Van der Stelt, M.J.C., Gerhauser, H., Kiel, J.H.A., Ptasiński, K.J.: Biomass upgrading by torrefaction for the production of biofuels: a review. *Biomass. Bioenergy* **35**, 3748–3762 (2011)
11. Rousset, P., Davrieux, F., Macedo, L., Perré, P.: Characterisation of the torrefaction of beech wood using NIRS: combined effects of temperature and duration. *Biomass. Bioenergy* **35**, 1219–1226 (2011)
12. Almeida, G., Brito, J.O., Perré, P.: Alterations of energy properties of eucalyptus wood and bark submitted to torrefaction: the potential of mass loss as a synthetic indicator. *Bioresour. Technol.* **101**, 9778–9784 (2010)
13. Biagini, E., Lippi, F., Petarca, L., Tognotti, L.: Devolatilization rate of biomasses and coal biomass blends: an experimental investigation. *Fuel* **81**, 1041–1050 (2002)
14. Fisher, T., Hajaligol, M., Waymack, B., Kellogg, D.: Pyrolysis behaviour and kinetics of biomass derived materials. *J. Anal. Appl. Pyrolysis* **62**, 331–349 (2002)
15. Bergman, P.C.A.: Torrefaction for entrained-flow gasification of biomass. In: *The 2nd World Conference and Technology Exhibition on Biomass for Energy, Industry and Climate Protection*, Rome, Italy (2004)
16. Prins, M.J., Ptasiński, K.J., Janssen, F.J.J.G.: Torrefaction of wood. Part 2. Analysis of products. *J. Anal. Appl. Pyrol.* **77**, 35–40 (2006)
17. Yan, W., Acharjee, T.C., Coronella, C.J., Vasquez, V.R.: Thermal pretreatment of lignocellulosic biomass. *Environ. Prog. Sustain. Energy* **28**, 435–440 (2009)
18. DD CEN/TS 14775:2004: Solid biofuels. Method for the determination of ash content, 2004. British Standards. p. 12
19. ECN-Biomass: Phyllis, database for biomass and waste. <http://www.ecn.nl/phyllis>